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ARDS User Manual

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INTRODUCTION

Personal computers (PCs) are now used extensively for engineering analysis; their capability exceeds that of mainframe computers of only a few years ago. Programs originally written for mainframes have been ported to PCs to make their use easier. One of these programs is ARDS (**A**nalysis of **R**otor**D**ynamic **S**ystems) which was developed at Arizona State University (ASU) by Nelson et al. to quickly and accurately analyze rotor steady state and transient response using the method of component mode synthesis (ref. 1). The original ARDS program was ported to the PC in 1995 and reported in reference 2. Several extensions were made at ASU to increase the capability of mainframe ARDS. These extensions were also incorporated into the PC version of ARDS and reported in reference 3. Each mainframe extension had its own user manual generally covering only that extension. Thus to exploit the full capability of ARDS required a large set of user manuals. Moreover, necessary changes and enhancements for PC ARDS were undocumented. The present document is intended to remedy those problems by combining all pertinent information needed for the use of PC ARDS into one volume.

PROGRAM DESCRIPTION

ARDS is a finite-element based digital computer program to analyze the free and forced response of multishaft rotor-bearing systems. The acronym ARDS denotes Analysis of Rotor Dynamic Systems. Systems with nonlinear interconnections and/or support bearings are analyzed by numerically integrating a reduced set of coupled system equations. Linear systems are analyzed in closed form for steady conditions and are treated the same as nonlinear systems for transient excitation.

The primary method of analysis in ARDS is based on the concept of component mode synthesis (CMS) or substructuring (refs. 1, 4 to 6). With linear systems, however, ARDS can also analyze the system by a direct method, at the option of the user. Direct analysis is always used for sensitivity studies and parameter optimization.

ARDS uses a fixed reference frame to describe the system motion. Therefore, it can accommodate nonsymmetric interconnections and nonsymmetric support stiffness and damping. With CMS, the interconnection and support bearings may also be nonlinear. The rotating assemblies are modeled as a number of finite elements each of which may have several subelements, thus allowing for flexibility in modeling systems with several geometric discontinuities. The rotating systems are assumed to be mounted on rigid foundations except for steady unbalance response using CMS where, optionally, dynamic flexibility properties of the foundation support points may be included. Detailed analyses pertaining to the extensions of ARDS are in references 7 to 10.

ARDS program options include analyses for:

1. Calculation of damped whirl frequencies and mode shapes

2. Calculation of damped and undamped critical speeds

3. Steady unbalance response. With the CMS option, the effect of foundation flexibility can also be included.

4. Steady response due to constant translational acceleration or constant turn rate (maneuver response)

5. Steady response due to external forces and moments

6. Transient response due to

   Step change in balance condition (e.g., blade loss);
   Arbitrary external forces;
   Step turns;
   Base acceleration

7. Estimate of peak response following sudden balance change without using full transient analysis

8. Calculation of response sensitivity to input parameter changes

9a. Determination of optimum rotor-bearing configuration to place critical speeds in desired ranges

9b. Optimization of squeeze film damper design to minimize bearing load

10. Production of Poincaré plots so presence of chaotic motion can be ascertained.

Restrictions and limitations of the current version of ARDS are given in appendix A.

DISCUSSION OF PROGRAM OPTIONS

1. Calculation of Damped Whirl Frequencies and Mode Shapes.—These are the natural frequencies of the shaft system, in forward and backward whirl, for the given shaft speeds. Forward and backward whirl frequencies differ because of gyroscopic effects. Output includes the real component of the whirl frequency which is a measure of stability (i.e., a positive real frequency component indicates a tendency to instability).

A kode 10 line calls for this analysis. (See **PROGRAM INPUT AND OUTPUT** section for use of the kode input method.)

2. Calculation of Damped and Undamped Critical Speeds.—A critical speed occurs when the speed of rotation equals a system natural frequency. Since the natural frequencies may themselves depend on speed of rotation (due to gyroscopic effects), determining a critical speed is an iterative process. ARDS makes use of sensitivity coefficients (discussed below) to carry this out. Details are in reference 8.

Damped critical speeds are obtained via a kode 15 line, and undamped critical speeds via a kode 81 line.

3. Steady Unbalance Response.—For specified unbalance distribution over a specified range of shaft speed. Output includes displacements at each rotor substation, load on each bearing, and, optionally, internal forces for each element.

This analysis is obtained via a kode 9 line. With the CMS option, foundation flexibility can be included with a kode 30 line.

4. Steady Response Due to Constant Translational Acceleration or Constant Turn Rate (Maneuvers).—This is the steady-state response relative to the rigid base when the foundation moves as specified. Output includes displacements and rotations at each rotor station, load on each bearing, and internal forces for each element.

This analysis is called by a kode 11 line.

5. Steady Response Due to External Forces and Moments.—Steady-state response relative to rigid base due to constant specified external forces or moments. Output is the same as for maneuvers (see no. 4 above).

This analysis is called by a kode 12 line.

6. Transient Response.—Due to (1) step change in balance condition (e.g., blade loss); (2) arbitrary external forces; (3) step turns; or (4) base acceleration. Transient analyses are performed only by CMS. All of the transient excitations specified are superposed, and the steady excitations of kodes 3, 4, and 11 are also superposed. Two nonlinear bearing types may be simulated: (1) rubs (kode 42); and (2) squeeze film dampers (kode 43).

A transient analysis is called by a kode 13 line, while the transient excitations are specified on one or more kode 14 lines.

7. Peak Blade Loss Response (Without Transient Analysis).—Transient vibration amplitudes following a suddenly applied rotor unbalance may be larger than subsequent steady-state vibration. Design of rotating machinery must account for this. Time transient analyses, such as performed by ARDS, can predict this vibration with good accuracy, but may be too time-consuming for the preliminary design phase. However, a quick approximation of the peak rotor displacement may be obtained using an analog of the shock spectrum analysis used in structural engineering. In concept, the response of each rotor mode to the sudden unbalance is obtained, and the responses then summed. This method has been implemented in ARDS, where four summation schemes are used: sum of the absolute values of the modes, a root-mean-square sum, and two combinations of these. The procedure is described in detail in reference 7.

Kodes 14 and 72 to 75 lines are used to obtain peak blade loss response.

8. Calculation of Response Sensitivity to Input Parameter Changes.—When designing a rotor system, it is often desirable to have a set of sensitivity coefficients which quantitatively predict a change in specific system characteristics as design parameters change. The dynamic characteristics of usual interest are the system whirl frequencies, the critical speeds, and steady unbalance response. With the finite element analysis used by ARDS, the sensitivity coefficients (partial derivatives of system characteristics with respect to parameter changes) can be calculated simply. The parameters considered are bearing coefficients, inertial properties of concentrated masses (discs), and the distributed mass and stiffness of the rotating shafts. Details of the procedure are in reference 8.

Sensitivity output is obtained via kodes 76 and 77 lines, and placing a sensitivity flag on kode 1, 2, 4 to 10, and 15 lines, as appropriate.

9. Optimum Rotor System Design.—Successful design of rotor systems requires the satisfaction of several operational constraints. Two of the more significant are placement of critical speeds (usually required to be outside the normal operating speed range) and minimization of bearing forces. Satisfying the first of these constraints is greatly facilitated by having sensitivity coefficients, described above. In theory, an optimum design could be formulated with the sensitivity coefficients and reanalysis using a cut-and-try process; however, the large number of design parameters makes this a daunting task. Use of available optimization codes makes the automation of the optimization process feasible.

ARDS casts the optimum design process as a nonlinear programming problem that minimizes an objective function subject to performance constraints and bounds on the design variables. The user of ARDS has a choice of optimization methods: recursive quadratic programming (RQP) or a feasible direction method (FDM). For the problems where the two methods were compared, FDM was more successful at reaching an optimum. For optimizing element length to place critical speeds, a third optimization technique not requiring derivatives is used. This technique, Conmax (ref. 11), was necessitated by an error in the derivative calculations in the original code that was not able to be eliminated.

Two types of problem have been programmed: (a) Placement of undamped critical speeds by optimization of bearing stiffness, shaft stiffness and mass, and bearing location. (b) Minimization of bearing load for steady unbalance response by optimization of squeeze film damper design. This can be done over a range of rotating speeds. In addition to the case where the damper is in parallel with the shaft bearings, ARDS can handle a series arrangement of damper and bearing, with a bearing mass interposed between the damper and bearing. Squeeze film properties are calculated using the short bearing approximation with cavitation assumed (π film). ARDS optimization techniques are described in references 9 and 10.

Critical speeds are placed using kodes 82 to 85 lines; Squeeze film dampers are optimized via kodes 90 to 94 lines.

10. Production of Poincaré Plots.—A Poincaré plot produces a picture similar to what one would see if the rotor were illuminated by a strobe light. That is, a Poincaré plot records the position of the rotor at periodic intervals, usually once per revolution. Poincaré plots are obtained as an optional form of x to y amplitude plots of transient analysis.

The plots are produced by requesting plot type 2 on the kodes 36 to 38 lines and specifying the proper plot multiple of the time step on the kode 13 line. The “kode” system is described in the next section.

PROGRAM INPUT AND OUTPUT

ARDS takes its input data from a text (ASCII) file. The user is prompted for the name of the file when ARDS is started. Printed output is sent to a text file; the user is also prompted for this output file name. Graphical output appears automatically on the monitor; it may be sent to a laser printer by typing “P” or “2” after the graph is on the screen.

Input data may be in any consistent set of units, e.g., SI. If customary U.S. units are used, force and mass units must be consistent. For example, if force is in pounds, mass must be in slugs or lb-sec^2/in. (depending on whether lengths are in feet or inches).

For most of the input a “kode” scheme is used in which the first field of a record (line) identifies the type of data. This makes the order of kode format input lines unimportant with one exception: if there is a possibility of data being overwritten, the last line read is the one used in the analysis. The first three input lines are not in kode format and must be in the order specified below. The last line of data for an analysis case must be either a kode 98 line, which indicates another case follows, or a kode 99 line, which signifies the present data is a termination case. For continuation cases, following a kode 98 line, only the second header line is input, followed by a control line. In addition, it is only necessary to input those lines that change the system description and request new analyses.

Kode values and their meaning are listed in appendix B. Examples of input data files and the output produced are given in appendix C.

Comment lines may be inserted into the input file anywhere after the two header lines. A comment line is identified by an asterisk (*) in column 1. These lines are echoed in the printed output, but are not used in the analysis.

In the input field descriptions that follow, 3-column fields require integer values that are right-justified; larger fields use real (floating point) numbers including a decimal point and, where needed, a right-justified exponent (power of 10). Any field left blank will be interpreted as zero. The present version of ARDS does not check for out-of-range data.

Run Designation Lines

- Header line 1: Up to 80 alphanumeric characters to identify the job

- Header line 2: Up to 80 alphanumeric characters to identify the analysis case

- Control line. Immediately follows header line 2 for each analysis case. It includes:

Field	Column	Data
1	1 to 3	Analysis option (0 = direct, 1 = CMS)
2	4 to 6	Optional system description output (0 = no, 1 = yes)
3	7 to 9	Optional system configuration plot (0 = no, 1 = yes)
4	10 to 12	Isotropic system indicator (0 = no, 1 = yes)
5	13 to 26	Not used
6	27 to 30	Suppress printout of kode and flag keys (0 = no, 1 = yes)

- Continuation line (kode 98)

  Field 1 (column 1 to 3) kode = 98

- Termination line (kode 99)

  Field 1 (column 1 to 3) kode = 99

System Description Lines

The shafts of the system are numbered consecutively from 1 to N_{shaft} and the finite element stations of the model are numbered consecutively starting with 1 at the left end of shaft 1 and continuing to the last station at the right end of shaft N_{shaft}. Element *i* is located immediately to the right of station *i*, as illustrated in figure 1, and the subelements of each element are numbered consecutively starting with 1 at the far left of the element. Note that an element does not exist for the last station of each shaft.

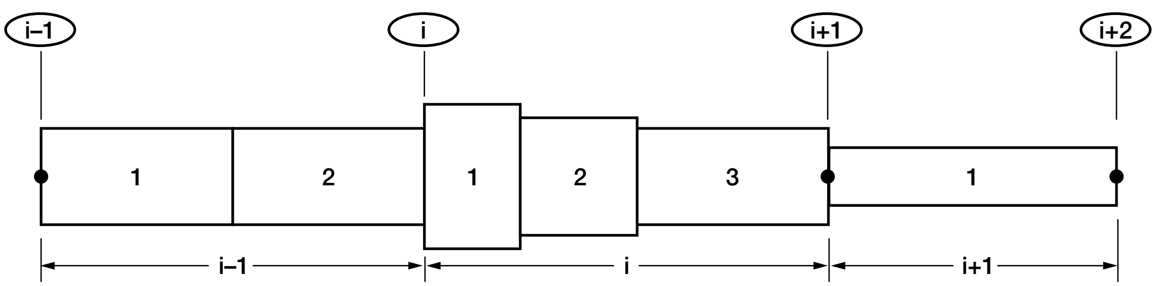

Figure 1.—Station, element, and subelement numbering.

- Rotor material data (kode 0)

Field	Column	Data
1	1 to 3	kode = 0
2	4 to 6	material data set number
3	7 to 9	blank
4	10 to 12	blank
5	13 to 24	density
6	25 to 36	elastic modulus
7	37 to 48	shear modulus
8	49 to 60	shape factor (correction factor for transverse shear, usually taken as 1.08)

- Subelement data (kode 1)

Field	Column	Data
1	1 to 3	kode = 1
2	4 to 6	element number
3	7 to 9	subelement number
4	10 to 12	sensitivity indicator (0 = no; 1 = yes)
5	13 to 24	length (zero for second level)
6	25 to 36	inner radius
7	37 to 48	outer radius
8	49 to 60	material data set number

- Concentrated mass data (kode 2)

Field	Column	Data
1	1 to 3	kode = 2
2	4 to 6	station number
3	7 to 9	blank
4	10 to 12	sensitivity indicator (0 = no; 1 = yes)
5	13 to 24	concentrated mass
6	25 to 36	diametral inertia
7	37 to 48	polar inertia

- Element unbalance (kode 3)

Field	Column	Data
1	1 to 3	kode = 3
2	4 to 6	first element number
3	7 to 9	last element number
4	10 to 12	blank
5	13 to 24	left end cg eccentricity
6	25 to 36	left end cg angle (degrees)
7	37 to 48	right end cg eccentricity
8	49 to 60	right end cg angle (degrees)

- Concentrated mass unbalance (kode 4)

Field	Column	Data
1	1 to 3	kode = 4
2	4 to 6	first station number
3	7 to 9	last station number
4	10 to 12	sensitivity indicator (0 = no; 1 = cg eccentricity; 2 = cg angle; 3 = both)

5	13 to 24	cg eccentricity
6	25 to 36	cg angle (degrees)

Cg eccentricities represent the distance from the rotational axis to the element center of mass; the angle is measured from the rotor y-axis.

Lines with kodes 5 to 8 represent bearing interconnections from station I to station J. J = 0 if the connection is from a shaft to the foundation. A standard (right-hand) x,y,z-coordinate system is used, with the x-axis coincident with the undeflected shaft axis. k_{yz} is a cross-coupled stiffness and represents the force in the y-direction due to a unit displacement in the z-direction; similarly, $k_{\beta\gamma}$ is a cross-coupled moment stiffness and represents the moment about the y-axis due to a unit rotation about the z-axis.

- Bearing translational stiffness (kode 5)

Field	Column	Data
1	1 to 3	kode = 5
2	4 to 6	station number I
3	7 to 9	station number J
4	10 to 12	sensitivity indicator (0 = no; 1 = yes)
5	13 to 24	k_{yy}
6	25 to 36	k_{yz}
7	37 to 48	k_{zy}
8	49 to 60	k_{zz}

- Bearing rotational stiffness (kode 6)

Field	Column	Data
1	1 to 3	kode = 6
2	4 to 6	station number I
3	7 to 9	station number J
4	10 to 12	sensitivity indicator (0 = no; 1 = yes)
5	13 to 24	$k_{\beta\beta}$
6	25 to 36	$k_{\beta\gamma}$
7	37 to 48	$k_{\gamma\beta}$
8	49 to 60	$k_{\gamma\gamma}$

- Bearing translational damping (kode 7)

Field	Column	Data
1	1 to 3	kode = 7
2	4 to 6	station number I
3	7 to 9	station number J
4	10 to 12	sensitivity indicator (0 = no; 1 = yes)
5	13 to 24	c_{yy}
6	25 to 36	c_{yz}
7	37 to 48	c_{zy}
8	49 to 60	c_{zz}

- Bearing rotational damping (kode 8)

Field	Column	Data
1	1 to 3	kode = 8
2	4 to 6	station number I
3	7 to 9	station number J

4	10 to 12	sensitivity indicator (0 = no; 1 = yes)
5	13 to 24	$c_{\beta\beta}$
6	25 to 36	$c_{\beta\gamma}$
7	37 to 48	$c_{\gamma\beta}$
8	49 to 60	$c_{\gamma\gamma}$

- Shear/moment release (kode 17)

Field	Column	Data	
1	1 to 3	kode = 17	
2	4 to 6	element number	
3	7 to 9	blank	
4	10 to 12	blank	
5	13 to 24	left end shear	
6	25 to 36	left end moment	1.0 = yes
7	37 to 48	right end shear	0 = no
8	49 to 60	right end moment	

- Element axial force (kode 18)

Field	Column	Data
1	1 to 3	kode = 18
2	4 to 6	left station number
3	7 to 9	right station number
4	10 to 12	blank
5	13 to 24	axial force (positive axial force is defined as tension)

- Element axial torque (kode 19)

Field	Column	Data
1	1 to 3	kode = 19
2	4 to 6	left station number
3	7 to 9	right station number
4	10 to 12	blank
5	13 to 24	axial torque

Positive axial torque, as defined by the right hand rule, points in the positive outward normal direction at the element boundary points

- Shaft description (kode 25) (one card per shaft required)

Field	Column	Data
1	1 to 3	kode = 25
2	4 to 6	shaft number
3	7 to 9	first station number of shaft
4	10 to 12	last station number of shaft
5	13 to 24	distance to first station from station 1

- Shaft spin speed (kode 26) (used only if kode 11, 12, or 13 analysis is requested)

Field	Column	Data
1	1 to 3	kode = 26
2	4 to 6	spin speed units (1 = rpm, 2 = rad/sec, 3 = Hz)
3	7 to 9	blank

4	10 to 12	blank
5	13 to 24	shaft 1 spin speed
6	25 to 36	shaft 2 spin speed or blank
7	37 to 48	shaft 3 spin speed or blank
8	49 to 60	shaft 4 spin speed or blank
9	61 to 72	shaft 5 spin speed or blank

- CMS shaft data (kode 27) (required for any CMS analysis; one line required for each shaft)

Field	Column	Data
1	1 to 3	kode = 27
2	4 to 6	shaft number I
3	7 to 9	no. of forward precessional modes retained for shaft I
4	10 to 12	no. of backward precessional modes retained for shaft I
5	13 to 24	low end of speed range for shaft I (rpm)
6	25 to 36	high end of speed range for shaft I (rpm)

- Foundation dynamic flexibility (kode 30) (required only if kode 29 analysis is requested) (input of an identically zero amplitude F(I,I,L) term will produce a system singularity)

Field	Column	Data
1	1 to 3	kode = 30
2	4 to 6	row I
3	7 to 9	column J
4	10 to 12	frequncy point L
5	13 to 24	frequency (L), Hz
6	25 to 36	amplitude F(I,J,L)
7	37 to 48	phase F(I,J,L), degrees

Data supplied by the kode 30 lines define graphs of log amplitude and linear phase versus log frequency for each of the system dynamic flexibility coefficients. ARDS uses a linear interpolation on these graphs to determine appropriate values of amplitude and phase at a specific shaft speed. Therefore, enough data points must be supplied to provide adequate accuracy. In addition, the frequency range of the data must cover the range specified in the kode 29 analysis request. A different number of data points may be used for each coefficient.

- Interference rub simulator (kode 42)

Field	Column	Data
1	1 to 3	kode = 42
2	4 to 6	station number
3	7 to 9	blank
4	10 to 12	blank
5	13 to 24	radial stiffness after contact occurs
6	25 to 36	rub friction coefficient
7	37 to 48	radial clearance before rubbing contact occurs

- Transient analysis squeeze film damper (kode 43) (uses short bearing theory with cavitation)

Field	Column	Data
1	1-3	kode = 43
2	4-6	station number
3	7-9	blank
4	10-12	blank

5	13-24	radial clearance
6	25-36	damper fluid viscosity
7	37-48	damper length
8	49-60	damper radius

Steady-state and transient analysis request lines

- Whirl speed/stability analysis (kode 10)

Field	Column	Data
1	1 to 3	kode = 10
2	4 to 6	shaft number
3	7 to 9	spin speed units (1 = rpm; 2 = rad/sec; 3 = Hz)
4	10 to 12	number of modes output (if negative, modes are also plotted)
5	13 to 24	initial spin speed
6	25 to 36	final spin speed
7	37 to 48	spin speed increment
8	49 to 60	sensitivity indicator (0 = no; 1.0 = yes)
9	61 to 72	spin speed sensitivity indicator (0 = no; 1.0 = yes)

- Undamped critical speed analysis (kode 81)

Field	Column	Data
1	1 to 3	kode = 81
2	4 to 6	number of critical speeds output
3	7 to 9	number of critical modes output
4	10 to 12	blank
5	13 to 24	shaft 1 spin to whirl ratio
6	25 to 36	shaft 2 spin to whirl ratio
7	37 to 48	shaft 3 spin to whirl ratio
8	49 to 60	shaft 4 spin to whirl ratio
9	61 to 72	shaft 5 spin to whirl ratio

- Steady unbalance response, rigid foundation (kode 9)

Field	Column	Data
1	1 to 3	kode = 9
2	4 to 6	shaft number
3	7 to 9	spin speed units (1 = rpm; 2 = rad/sec; 3 = Hz)
4	10 to 12	internal force optional output (0 = no; 1 = yes)
5	13 to 24	initial spin speed
6	25 to 36	final spin speed
7	37 to 48	spin speed increment
8	49 to 60	sensitivity indicator (0 = no; 1.0 = yes)

- Damped critical speed analysis (kode 15)

Field	Column	Data
1	1 to 3	kode = 15
2	4 to 6	shaft number
3	7 to 9	number of critical speeds to be calculated, N_{cr}
4	10 to 12	blank
5	13 to 24	spin/whirl ratio αd_i

6	25 to 36	constant guess αf_i
7	37 to 48	initial guess of spin speed Ω^* (rad/sec)
8	49 to 60	sensitivity indicator (0 = no; 1.0 = yes)
9	61 to 72	acceptable tolerance $\Delta\Omega_{acc}$

- Steady unbalance response, flexible foundation (kode 29) (kode 30 input also required)

Field	Column	Data
1	1 to 3	kode = 29
2	4 to 6	shaft number
3	7 to 9	spin speed units (1 = rpm; 2 = rad/sec; 3 = Hz)
4	10 to 12	internal force optional output (0 = no; 1 = yes)
5	13 to 24	initial spin speed
6	25 to 36	final spin speed
7	37 to 48	spin speed increment
8	49 to 60	optional output of foundation support coordinates (0 = no; 1.0 = yes)

- Whirl frame unbalance response (kode 16) (requires kode 26 input also)

Field	Column	Data
1	1 to 3	kode = 16
2	4 to 6	shaft number
3	7 to 9	spin speed units (1 = rpm; 2 = rad/sec; 3 = Hz)
4	10 to 12	internal force indicator (0 = no; 1 = yes)
5	13 to 24	initial spin speed
6	25 to 36	final spin speed
7	37 to 48	spin speed increment

- Steady maneuver (kode 11) (requires kode 26 input also)

Field	Column	Data
1	1 to 3	kode = 11
2	4 to 6	maneuver type (0 = turnrate; 1 = acceleration)
3	7 to 9	blank
4	10 to 12	blank
5	13 to 24	base translational acceleration
6	25 to 36	acceleration angle, degrees
7	37 to 48	base turn rate (red/sec)
8	49 to 60	turn angle, degrees

- Static loads or force multipliers (kode 12) (requires kode 26 input also; force multipliers are used when specified variable forces are included in transient analysis request (kode 13)

Field	Column	Data
1	1 to 3	kode = 12
2	4 to 6	station number
3	7 to 9	0 = static loads; 1 = force multipliers
4	10 to 12	blank
5	13 to 24	F_Y
6	25 to 36	F_Z
7	37 to 48	M_Y
8	49 to 60	M_Z

- Squeeze film centered circular orbit analysis (kodes 23 and 24)

Squeeze film damper parameters (kode 23)

Field	Column	Data
1	1 to 3	kode = 23
2	4 to 6	station number
3	7 to 9	series/parallel indicator*
4	10 to 12	relaxation factor/100 for iterations in squeeze film solver
5	13 to 24	length
6	25 to 36	radius
7	37 to 48	radial clearance
8	49 to 60	damper fluid viscosity
9	61 to 72	pedestal (damper) mass
10	73 to 80	damper centering spring stiffness

* Series parallel indicator:

0 Squeeze film and collocated bearing in parallel. Objective function = $\Sigma w_i \mid F_{sfi} + F_{bi} \mid$ where F_{sfi} and F_{bi} are the forces reacted by the squeeze film and bearing, respectively, at station i. w_i = weight factor from kode 92 input.

≥ 1 Squeeze film and collocated bearing in series.

1 Objective function = $\Sigma w_i (\mid F_{sf\,i} \mid + \mid F_{bi} \mid)$

2 Objective function = $\Sigma w_i \mid F_{bi} \mid$

3 Objective function = $\Sigma\, w_i \mid F_{sf\,i} \mid$

Objective functions are calculated only for kode 90 analysis.

System data (kode 24)

Field	Column	Data
1	1 to 3	kode = 24
2	4 to 6	shaft number with unbalance
3	7 to 9	spin speed units (1-rpm; 2-rad/sec; 3-Hz)
4	10 to 12	maximum number of iterations (negative for kode 90 analysis)
5	13 to 24	initial spin speed
6	25 to 36	final spin speed
7	37 to 48	spin speed increment
8	49 to 60	initial eccentricity ratio
9	61 to 72	error criterion
10	73 to 80	addendum to iteration limit

- Transient analysis request (kode 13) (requires kode 14 and kode 26 input)

Field	Column	Data
1	1 to 3	kode = 13
2	4 to 6	print multiple of time step
3	7 to 9	plot multiple of time step
4	10 to 12	blank
5	13 to 24	fixed interval time step
6	25 to 36	final time

Transient analyses are performed only by the CMS approach. All of the various transient excitations specified in the input (kode 14) are superposed. The steady excitations of kodes 3 and 4 (unbalance), and kode 11 (steady maneuver) are also superposed on the transient excitations.

- Transient analysis excitation or blade loss spectrum analysis request (kode 14)

Field	Column	Data				
1	1 to 3	kode = 14				
		Step turn	Variable base acceleration table	Variable specified force table	Blade loss and/or distributed unbalance[2]	Blade loss spectrum analysis
2	4 to 6	1	2	3	4	5 or 6[4]
3	7 to 9	blank	blank	blank	Station no.	Station no.
4	10 to 12	blank	Time pt. no. i	Time pt. no. i	Distributed unbalance indicator (0-no; 1-yes)[3]	No. of analysis spin speeds (48 maximum)
5	13 to 24	Turn rate, degrees	Time, T_i	Time, T_i	Blade loss mass	Blade loss station mass
6	25 to 36	Turn angle β_f	Accel. A_i	Force F_i	Blade loss cg eccentricity	Blade loss station cg eccentricity
7	37 to 48	Start time of turn T_s	Accel. angle α_f [1]	blank	Blade loss angle	Blade loss station cg angle
8	49 to 60	blank	blank	blank	Blade loss time	Initial spin speed Ω_I
9	61 to 72	blank	blank	blank	blank	Final spin speed Ω_F

[1]Necessary only for time point i = 1.
[2]Only the shaft unbalances associated with the station number entered on this input line are included in the RHS.
[3]Unbalances associated with kodes 3 and 4.
[4]5 denotes system modes obtained by eigenanalysis at each spin speed; 6 denotes system modes obtained by quadratic curve fit.

- Transient analysis output selection (kode 35)

If a kode 35 line is not included, the transient output defaults to the displacement and velocity response at each finite element station. Two types of output are allowed per case at each time step. They are designated as follows:

1. Displacement
2. Velocity
3. Support forces
4. Internal element shears
5. Internal element moments

Field	Column	Data
1	1 to 3	kode = 35
2	4 to 6	First output type
3	7 to 9	Second output type

- Transient analysis plots: displacement (kode 36), velocity (kode 37), or support force (kode 38)

Displacement and/or velocity plots may be made at user-specified finite element stations. Two displacement or two velocity variables may be plotted versus time or may be cross plotted. Only one kode 36 input line, one kode 37 input line, and one kode 38 input line are allowed for each station.

Field	Column	Data
1	1 to 3	kode = 36 (displacement), kode = 37 (velocity), or kode = 38 (support force)
2	4 to 6	station number
3	7 to 9	plot type (0 = time; 1 = cross; 2 = Poincaré cross plot)
4	10 to 12	blank
5	13 to 24	first variable type

6	25 to 36	first variable plot scale
7	37 to 48	second variable type
8	49 to 60	second variable plot scale

Plot variable type (for fields 5 and 7)

1 y-translation
2 z-translation
3 y-rotation
4 z-rotation

If field 3 is zero, the first variable and second variable are both plotted versus time. If field 3 is 1, the first variable is plotted versus the second variable.

- Transient analysis initial condition (kode 39)

If a kode 39 line is not included in the input data, the transient analysis initial conditions default to zero for both displacement and velocity. Initial conditions are only input at rotor support stations; the program determines initial conditions at other stations based on the concept of static constraint modes.

Field	Column	Data
1	1 to 3	kode = 39
2	4 to 6	indicator (0 = displacements; 1 = velocities)
3	7 to 9	station number
4	10 to 12	blank
5	13 to 24	y-translation
6	25 to 36	z-translation
7	37 to 48	y-rotation
8	49 to 60	z-rotation

<u>Blade loss response spectrum analysis</u>

A spectrum analysis is requested by a kode 14 line which is also used to specify excitation for transient analyses (see that section for format of kode 14 line). On that line, type 5 analysis calculates system modes by a separate eigenanalysis at each spin speed. Type 6 analysis allows the modes to be obtained by a quadratic curve fit using modal values at three spin speeds Ω_I, $(\Omega_I + \Omega_F)/2$, and Ω_F. If the modes are not changing rapidly in shape, a type 6 analysis is recommended for higher computation speed. A type 5 analysis should be used for greater accuracy in spin speed intervals where the mode shapes are changing rapidly.

A kode 71 line is also required to specify the spectrum to be used and to indicate the system precessional modes to be included. A separate whirl speed analysis would usually need to be conducted prior to the blade loss spectrum analysis in order to gain the insight required to select the modes. A maximum of 4 kode 71 lines (i.e., a maximum of 20 precessional modes) may be used for each blade loss spectrum analysis.

- Spectrum generation precession mode selection (kode 71)

Field	Column	Data
1	1 to 3	kode = 71
2	4 to 6	spectra generation indicator 0 - generate new spectra, do not save 1 - generate new spectra and save them 2 - read previously generated spectra

3	7 to 9	blank
4	10 to 12	blank
5	13 to 24	precession mode number
6	25 to 36	precession mode number
7	37 to 48	precession mode number
8	49 to 60	precession mode number
9	61 to 70	precession mode number

A 2 entry in field 2 indicates that previously generated progressive and retrograde spectra will be used in the analysis. If 0 or 1 is specified in field 2, new progressive and retrograde spectra are generated and then used in the analysis. The spin ratios and damping ratios used in the spectra generation are specified by kodes 72 and 73 lines, respectively. If spin ratios are not specified (i.e., no kode 72 data), then the default values are 20 spin speed ratios with ρ_i = 0.10, 0.25, 0.35, 0.50, 0.65, 0.75, 0.85, 0.90, 0.95, 1.00, 1.05, 1.10, 1.15, 1.20, 1.30, 1.40, 1.70, 2.00, 5.00, 10.00. If the damping values are not specified (i.e., no kode 73 data), then the default values are: ζ_i = 0.0001, 0.001, 0.01, 0.035, 0.07, 0.15, 0.20, 0.25, 0.35, 0.45, 0.50, 0.55, 0.60, 0.65, 0.70, 0.75, 0.80, 0.90, 0.95, 0.99.

The peak response due to a blade loss may also be obtained by running a time transient analysis and recording the peak response. This option is available in ARDS by means of a kode 74 line. Use of this option may result in long run times, so care should be exercised in its usage. In the neighborhood of critical speeds, a large number of cycles (e.g., 10 to 50) may be required before the peak response is reached. Away from the critical speeds, normally only a few cycles (less than 5) are required to locate the peak response. A “true peak” response request (kode 74) may be made in the same run with a spectrum response request (kodes 14 and 71).

The data fields for kodes 72 to 74 lines are given below.

- Spectrum generation spin ratios (kode 72) (maximum of 4 lines)

Field	Column	Data
1	1 to 3	kode = 72
2	4 to 6	total number of spin ratios N_{SR}
3	7 to 9	first spin ratio number on this line N_f
4	10 to 12	last spin ratio number on this line N_l ($N_l \le N_f + 4$)
5	13 to 24	spin ratio N_f
6	25 to 36	spin ratio $N_f + 1$
7	37 to 48	spin ratio $N_f + 2$
8	49 to 60	spin ratio $N_f + 3$
9	61 to 72	spin ratio $N_f + 4$

- Spectrum generation damping ratios (kode 73) (maximum of 4 lines)

Field	Column	Data
1	1 to 3	kode = 73
2	4 to 6	total number of damping ratios N_{SR}
3	7 to 9	first damping ratio number on this line N_f
4	10 to 12	last damping ratio number on this line N_l ($N_l \le N_f + 4$)
5	13 to 24	damping ratio N_f
6	25 to 36	damping ratio $N_f + 1$
7	37 to 48	damping ratio $N_f + 2$
8	49 to 60	damping ratio $N_f + 3$
9	61 to 72	damping ratio $N_f + 4$

- True peak response request (kode 74)

Field	Column	Data
1	1 to 3	kode = 74
2	4 to 6	station number (one line required for each station)
3	7 to 9	translation coordinates output (0 = no; 1 = yes)
4	10 to 12	rotation coordinates output (0 = no; 1 = yes)
5	13 to 24	maximum number of cycles used in search

Plots of peak responses may be obtained by including a kode 75 line for each station where plotted output is desired. Any or all of the four absolute station displacements (Y, Z translations and rotations) may be requested. When ARDS executes the user will be prompted for the name of a file to receive the plotable data. Actual plots are then made by calling the program SPECPLOT.

- Blade loss spectrum analysis plot request (kode 75)

Field	Column	Data
1	1 to 3	kode = 75
2	4 to 6	plot type (+1= linear-linear; –1 = log-linear)
3	7 to 9	station number
4	10 to 12	number of coordinates requested for this station
5	13 to 24	first coordinate
6	25 to 36	second coordinate
7	37 to 48	third coordinate
8	49 to 60	fourth coordinate

Coordinate identification: Y-translation = 1, Z-translation = 2, Y-rotation = 3, Z-rotation = 4.

<u>Response sensitivity analysis</u>

ARDS can calculate the sensitivity of several output parameters to changes in numerous input parameters. The output parameters are whirl speeds/stability, damped critical speeds, and stead unbalance response. The input parameters are, as appropriate, subelement dimensions, concentrated masses, unbalance, and bearing translational and rotational stiffness and damping.

Input parameters for which sensitivity data are desired are specified by entering the appropriate sensitivity indicator on kodes 1, 2, and 4 to 8 lines. Output parameters for which sensitivity results are desired are specified by entering the appropriate sensitivity indicator on kode 9, 10, and 15 lines.

The direct method of analysis must be specified for sensitivity analyses.

Sensitivity coefficients as calculated by ARDS are derivatives. To make the output more meaningful, these derivatives may be multiplied by some assumed change in the input parameters. This may be done through input of a kode 77 line. Three kode 77 lines are needed to input multipliers for all of the input parameters. If a kode 77 line is not included for a parameter the multiplier is 1.

- Multipliers for sensitivity analysis (kode 77)

Field	Column	Data		
1	1 to 3	kode = 77	kode = 77	kode = 77
2	4 to 6	1	2	3
3	7 to 9	blank	blank	blank
4	10 to 12	blank	blank	blank

5	13 to 24	m_d	K_{Tr}	ℓ
6	25 to 36	I_d	K_{Ro}	ρA
7	37 to 48	I_p	C_{Tr}	EI
8	49 to 60	cg ecc.	C_{Ro}	blank
9	61 to 72	cg angle	blank	blank

Nomenclature for sensitivity factor multipliers

C_{Ro}	bearing moment damping	K_{Ro}	bearing moment stiffness
C_{Tr}	bearing translational damping	K_{Tr}	bearing translational stiffness
EI	subelement bending stiffness	ℓ	subelement length
I_d	disc diametral inertia	m_d	disc mass
I_p	disc polar inertia	ρA	subelement mass/unit length

For unbalance response sensitivity, up to 5 output stations may be specified by a kode 76 line. If this line is not included, output will be for all output stations.

- Unbalance response sensitivity output (kode 76)

Field	Column	Data
1	1 to 3	kode = 76
2	4 to 6	number of output stations (≤5)
3	7 to 9	blank
4	10 to 12	blank
5	13 to 24	first output station
6	25 to 36	second output station
7	37 to 48	third output station
8	49 to 60	fourth output station
9	61 to 72	fifth output station

Optimization of design

- Undamped critical speed optimization (kodes 82 to 86)

Basic options (kode 82)

Field	Column	Data
1	1 to 3	kode = 82
2	4 to 6	optimization method (1 = RQP, 2 = FDM)
3	7 to 9	number of design parameters
4	10 to 12	number of design critical speeds
5	13 to 24	maximum number of iterations
6	25 to 36	convergence criterion
7	37 to 48	design variable indicator 1 - bearing stiffness 2 - element inner radius 3 - element outer radius 4 - element length 5 - position of bearing support

Spin speed operating range (kode 83)

Field	Column	Data
1	1 to 3	kode = 83
2	4 to 6	design critical speed number, m
3	7 to 9	spin speed units (1 = rpm; 2 = rad/sec; 3 = Hz)
4	10 to 12	blank
5	13 to 24	upper bound for critical speed m
6	25 to 36	lower bound for critical speed m + 1

Design parameter limits (for design variable selected with kode 82) (kode 84)

Field	Column	Data
1	1 to 3	kode = 84
2	4 to 6	element number
3	7 to 9	subelement number
4	10 to 12	station number
5	13 to 24	lower bound
6	25 to 36	upper bound

Weight factors for critical speed placement (kode 85)

Field	Column	Data
1	1 to 3	kode = 85
2	4 to 6	critical speed number, m
3	7 to 9	spin speed units (1 = rpm; 2 = rad/sec; 3 = Hz)
4	10 to 12	blank
5	13 to 24	weight factor
6	25 to 36	desired critical speed value

Spin to whirl ratio (kode 86)

Field	Column	Data
1	1 to 3	kode = 86
2	4 to 6	blank
3	7 to 9	blank
4	10 to 12	blank
5	13 to 24	shaft 1 spin to whirl ratio
6	25 to 36	shaft 2 spin to whirl ratio
7	37 to 48	shaft 3 spin to whirl ratio
8	49 to 60	shaft 4 spin to whirl ratio
9	61 to 72	shaft 5 spin to whirl ratio

- Squeeze film design optimization (kodes 24, 90 to 94)

Basic options (kode 90)

Field	Column	Data
1	1 to 3	kode = 90
2	4 to 6	optimization method (1 = RQP, 2 = FDM)
3	7 to 9	number of design dampers
4	10 to 12	number of design support loads
5	13 to 24	number of inequality constraints*

6	25 to 36	maximum number of iterations
7	37 to 48	convergence criterion
8	49 to 60	optimization type (1.–design at specified spin speed; 2.–design over a range of speeds)

* For design at a single spin speed, additional inequality constraints may be imposed via kode 93 lines to limit the eccentricity ratio of the damper(s). For design over a range of speeds, set the number of inequality constraints to zero.

Damper design parameter limits (maximum of 4 lines per damper) (kode 91)

Field	Column	Data
1	1 to 3	kode = 91
2	4 to 6	station number
3	7 to 9	parameter indicator (1–radius, 2–length, 3–radial clearance, 4–centering spring stiffness)
4	10 to 12	blank
5	13 to 24	lower bound
6	25 to 36	upper bound

Weight factors for bearing loads (kode 92)

Field	Column	Data
1	1 to 3	kode = 92
2	4 to 6	station number
3	7 to 9	blank
4	10 to 12	blank
5	13 to 24	weight factor

Eccentricity ratio inequality constraint data (kode 93)

Field	Column	Data
1	1 to 3	kode = 93
2	4 to 6	damper station number
3	7 to 9	blank
4	10 to 12	blank
5	13 to 24	maximum eccentricity ratio allowed (<1.0)

Artificial design variable (kode 94)

Field	Column	Data
1	1 to 3	kode = 94
2	4 to 6	blank
3	7 to 9	blank
4	10 to 12	blank
5	13 to 24	initial guess value
6	25 to 36	lower bound
7	37 to 48	upper bound

The artificial design variable represents the maximum transmitted bearing load. Both the initial guess and the upper bound can be set to the value determined in a preliminary analysis of the system. The lower bound can be set to a small positive number, e.g., 0.01.

APPENDIX A

PROGRAM IMPLEMENTATION

I. FORTRAN Logical Units

The following logical units are used by ARDS

5	Input
6	Output

II. Restrictions and limitations of ARDS

The following limitations apply in the current structure of ARDS:

- Maximum of 5 shafts.
- Maximum of 21 stations (total) when direct method of analysis is used.
- Maximum of 11 stations per shaft (55 total stations) when CMS method is used.
- ARDS will not detect the need to recalculate component modes if bearing locations are changed in continuation cases. However, if the rotating assembly is changed, the component modes are recalculated.

APPENDIX B

KODE KEY

See index for page numbers

0	Rotor material data
1	Subelement data
2	Concentrated mass data
3	Element unbalance data
4	Concentrated mass unbalance data
5	Bearing translational stiffness
6	Bearing rotational stiffness
7	Bearing translational damping
8	Bearing rotational damping
9	Unbalance response and sensitivity
10	Whirl speed analysis and sensitivity
11	Steady maneuver analysis
12	Static loads or force multipliers
13	Transient analysis
14	Transient analysis excitation or spectrum analysis
15	Damped critical speed and sensitivity
16	Whirl frame unbalance response
17	Shear/moment release
18	Element axial force data
19	Element axial torque data
20 to 22	Unassigned
23	Squeeze film damper parameters
24	Squeeze film centered circular orbit analysis
25	Shaft description
26	Shaft spin speed for kode 11, 12, or 13 analysis
27	CMS shaft data
28	Unassigned
29	CMS unbalance response, flexible foundation
30	Flexible foundation data
31 to 33	Unassigned
34	Optional transient output
35	Transient analysis output selection
36	Transient analysis displacement plot
37	Transient analysis velocity plot
38	Transient analysis force plot
39	Transient analysis initial condition
40 to 41	Unassigned
42	Rub simulator
43	Squeeze film damper
44 to 70	Unassigned
71	Blade loss spectrum analysis
72	Spectrum analysis spin speed ratios
73	Spectrum analysis damping ratios data
74	Spectrum analysis true peak response
75	Blade loss spectrum analysis plot
76	Unbalance response sensitivity output
77	Multipliers for sensitivity analysis

78 to 80	Unassigned
81	Undamped critical speed analysis request
82	Critical speed optimization options
83	Critical speed optimization speed range
84	Critical speed optimization parameter limits
85	Critical speed optimization weight factors
86	Spin to whirl ratio
87 to 89	Unassigned
90	Squeeze film optimization data
91	Squeeze film optimization parameter limits
92	Squeeze film optimization weight factors
93	Squeeze film optimization eccentricity limits
94	Squeeze film optimization artificial design variable
95 to 97	Unassigned
98	Continuation case to follow
99	Termination of run

APPENDIX C

EXAMPLES OF ARDS ANALYSES

Example 1. Precessional modes and unbalance response

A small rotordynamics demonstrator rotor capable of 10 000 rpm was modeled for this exercise. Two electromagnetic bearings were fitted to the rotor; an O-ring supported bronze bushing was also used for rotor support. An outline of the rotor configuration, drawn by ARDS, appears as figure 2. As the figure shows, the rotor was modeled with 9 elements resulting in 10 rotor stations. Some of these elements are composed of multiple subelements. Concentrated masses are attached to the shaft at 5 of the stations. The magnetic bearings are at stations 3 and 7; however, only the bearing at station 3 with a stiffness of 44 kN/m (250 lb/in.) was active for this example. Magnetic bearings are customarily used with "backup" bearings which can support the rotor in the event of magnetic bearing failure. A backup bearing in the form of a loose bushing is modeled in addition to the magnetic bearing at station 3. The backup bearing is therefore nonlinear in that the stiffness is zero until the 0.25 mm (0.010 in.) radial clearance is taken up. It is then assumed to have a stiffness of 880 kN/m (5000 lb/in.) in the radial direction; the tangential force is calculated as the radial force times a friction coefficient. This bearing model is built into ARDS for calculation of events such as blade loss with ensuing rubs; it is invoked via kode 42. The bronze bushing supports the shaft at station 8; its stiffness was 175 kN/m (1000 lb/in.).

As mentioned, ARDS accepts input in any consistent set of units. The units used in this example for length, force, time, and mass are inches, pounds, seconds, and lb sec^2/in., respectively. Corresponding SI units are meters, newtons, seconds, and kilograms. Table I shows the rotor properties in the in.-lb-sec units employed. The values shown for mass and inertia are in addition to those the program calculates from the rotor dimensions. The example rotor is made of steel; thus the elastic modulus and density of steel were among the input to the program. The ARDS input file appears as figure 3. An excerpt of the corresponding output file is shown in figure 4.

Figure 5 shows the ARDS plot of the first precessional mode for the example rotor at a spin speed of 5000 rpm; the precessional frequency is 1504 rpm. The amplitude scale is normalized such that the maximum amplitude is unity. The printed output notes that this is a backward mode (semiminor axis is negative); the first forward mode is of similar shape and occurs at 1539 rpm. Other modes within the 10 000

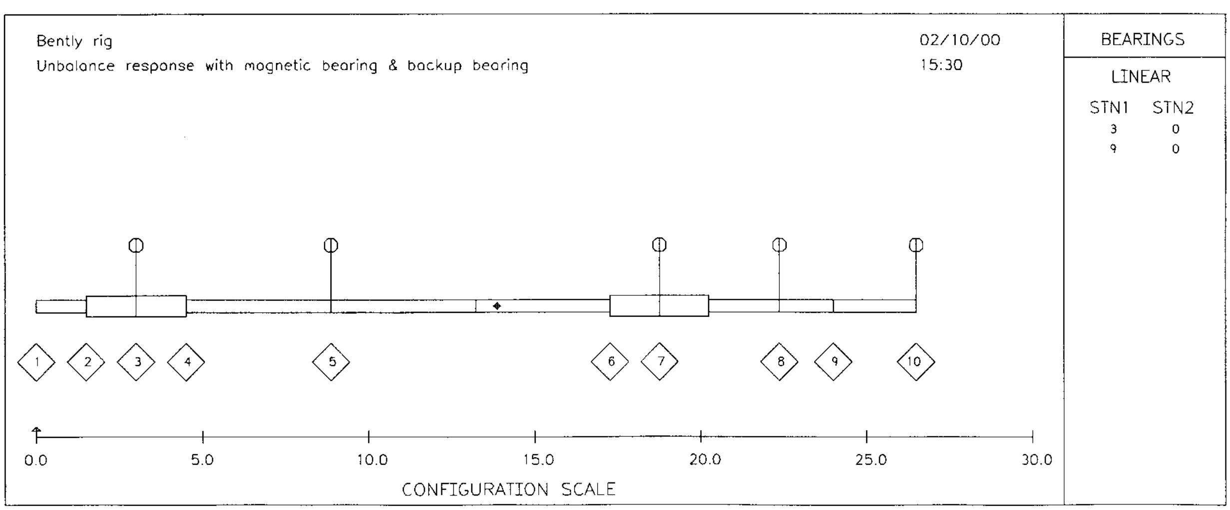

Figure 2.—ARDS drawing of example 1 rotor.

TABLE I.—ROTOR PHYSICAL PROPERTIES

Station number	Subelement number	Length, in.	Radius, in.	Mass, lb-sec^2/in.	Diametral inertia, lb-in.-sec^2	Polar inertia, lb-in.sec^2
1	1	1.5	0.1875			
2	1	1.5	.3125			
3	1	1.5	.3125	0.00207	0.00057	0.00114
4	1	4.375	.1875			
5	1	4.375	.1875	.00383	.00218	.00437
	2	4	.1875			
6	1	1.5	.3125			
7	1	1.5	.3125	.00207	.00057	.00114
	2	2.125	.1875			
8	1	1.625	.1875	.00383	.00218	.00437
9	1	2.5	.1875			
10				.00025		

```
Bently rig
Unbalance response with magnetic bearing & backup bearing
* Two header lines begin input file
  1  1  1  1
* Previous line is control line; must be used.
* Next line (kode=0) gives material properties.
  0  1      .000733     30000000.   15400000.   1.08
* Kode 25 line(s) designates number of stations for each shaft.
 25  1  1 10 0.
* Kode 26 line provides spin speeds of shafts.
 26  1      5000.
* Kode 27 line designates number of precessional modes used in analysis.
 27  1  2  2 1000.      10000.
* Kode 1 lines give geometry of shaft subelements.
  1  1  1        1.5                  .1875    1.
  1  2  1        1.5                  .3125    1.
  1  3  1        1.5                  .3125    1.
  1  4  1        4.375                .1875    1.
  1  5  1        4.375                .1875    1.
  1  5  2        4.                   .1875    1.
  1  6  1        1.5                  .3125    1.
  1  7  1        1.5                  .3125    1.
  1  7  2        2.125                .1875    1.
  1  8  1        1.625                .1875    1.
  1  9  1        2.5                  .1875    1.
* Kode 2 lines provide data for concentrated masses.
  2  3        .00207      .00057      .00114
  2  5        .00383      .00218      .00437
* Kode 4 lines show unbalance of concentrated masses.
  4  5  5    .0001
  2  7        .00207      .00057      .00114
  2  8        .00383      .00218      .00437
  4  8  8    .0001       90.
  2 10        .00025
* Kode 5 lines give bearing translational stiffnesses.
  5  3        250.                          250.
  5  9        1000.                         1000.
* Kode 7 lines provide bearing translational damping.
  7  3        1.                              1.
  7  9        2.                              2.
* Kode 9 calls steady unbalance response analysis.
  9  1  1  0 2500.      10000.      2500.
* Kode 10 calls whirl speed/stability analysis.
 10  1  1 -8 5000.      5000.       4500.
* Kode 99 ends this job.
 99
```

Figure 3.—ARDS input for example 1.

****

ARDS - Analysis of Rotor-Dynamic Systems

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Dept. of Engineering Sciences, ASU, Tempe Arizona
Adapted to PC by D. P. Fleming, NASA Glenn Research Center, 1995-1997

****

Input file = magman5.dat   02/10/00   15:30

Bently rig

Unbalance response with magnetic bearing & backup bearing

SUMMARY OF INPUT DATA AND SYSTEM MODEL PARAMETERS
****

********** THE SYSTEM TO BE ANALYZED IS MODELED WITH **********

1 SHAFT(S), 9 ELEMENTS, 11 SUBELEMENTS, 10 STATIONS,
5 CONCENTRATED MASSES, 2 LINEAR SUPPORTS, 0 NONLINEAR SUPPORTS

********** EQUIVALENT RIGID BODY PROPERTIES **********

SHAFT NUMBER	MASS	CM LOCATION	POLAR INERTIA	DIAMETRAL INERTIA	LENGTH
1	0.1506E-01	13.89	0.1112E-01	0.9002	26.50

********** METHOD OF ANALYSIS -- COMPONENT MODE SYNTHESIS **********

SHAFT NO	PRECESSIONAL MODES RETAINED FORWARD	BACKWARD	SPIN SPEED RANGE (RPM) *** LOW ****	*** HIGH ***
1	2	2	1000.00	10000.0

********** CROSS SECTION PROPERTIES **********

PROPERTY NO.	VOLUME DENSITY	ELASTIC MODULUS	SHEAR MODULUS	SHAPE FACTOR
1	0.7330E-03	0.3000E+08	0.1540E+08	1.080

********** SUBELEMENT PARAMETERS **********

ELEM NO	SUB ELEM NO	LEFT END LOC	LENGTH	***LEVEL ONE*** INNER RADIUS	OUTER RADIUS	***LEVEL TWO*** INNER RADIUS	OUTER RADIUS	UNIT MASS	UNIT BENDING STIFFNESS	LEFT CG ECCEN	LEFT CG ANGLE	RIGHT CG ECCEN	RIGHT CG ANGLE
SHAFT 1													
1	1	0.000	1.500	0.000	0.188	0.000	0.000	0.8096E-04	0.2912E+05	0.0000	0.000	0.0000	0.000
2	1	1.500	1.500	0.000	0.313	0.000	0.000	0.2249E-03	0.2247E+06	0.0000	0.000	0.0000	0.000
3	1	3.000	1.500	0.000	0.313	0.000	0.000	0.2249E-03	0.2247E+06	0.0000	0.000	0.0000	0.000
4	1	4.500	4.375	0.000	0.188	0.000	0.000	0.8096E-04	0.2912E+05	0.0000	0.000	0.0000	0.000
5	1	8.875	4.375	0.000	0.188	0.000	0.000	0.8096E-04	0.2912E+05	0.0000	0.000	0.0000	0.000
	2	13.250	4.000	0.000	0.188	0.000	0.000	0.8096E-04	0.2912E+05	0.0000	0.000	0.0000	0.000
6	1	17.250	1.500	0.000	0.313	0.000	0.000	0.2249E-03	0.2247E+06	0.0000	0.000	0.0000	0.000
7	1	18.750	1.500	0.000	0.313	0.000	0.000	0.2249E-03	0.2247E+06	0.0000	0.000	0.0000	0.000
	2	20.250	2.125	0.000	0.188	0.000	0.000	0.8096E-04	0.2912E+05	0.0000	0.000	0.0000	0.000
8	1	22.375	1.625	0.000	0.188	0.000	0.000	0.8096E-04	0.2912E+05	0.0000	0.000	0.0000	0.000
9	1	24.000	2.500	0.000	0.188	0.000	0.000	0.8096E-04	0.2912E+05	0.0000	0.000	0.0000	0.000

Figure 4.—ARDS output for example 1.

********** BEARING STIFFNESS COEFFICIENTS **********

STN NO1	STN NO2	KVV	KVW	KWV	KWW	KBB	KBG	KGB	KGG
		*************** TRANSLATIONAL ***************				**************** ROTATIONAL ****************			
3	0	250.0	0.0000	0.0000	250.0	0.0000	0.0000	0.0000	0.0000
9	0	1000.	0.0000	0.0000	1000.	0.0000	0.0000	0.0000	0.0000

********** BEARING DAMPING COEFFICIENTS **********

STN NO1	STN NO2	CVV	CVW	CWV	CWW	CBB	CBG	CGB	CGG
		*************** TRANSLATIONAL ***************				**************** ROTATIONAL ****************			
3	0	1.000	0.0000	0.0000	1.000	0.0000	0.0000	0.0000	0.0000
9	0	2.000	0.0000	0.0000	2.000	0.0000	0.0000	0.0000	0.0000

********** CONCENTRATED MASS PARAMETERS **********

STN NO	MASS	DIAMETRAL INERTIA	POLAR INERTIA	CG ECCEN	CG ANGLE
3	0.2070E-02	0.5700E-03	0.1140E-02	0.0000	0.0000
5	0.3830E-02	0.2180E-02	0.4370E-02	0.1000E-03	0.0000
7	0.2070E-02	0.5700E-03	0.1140E-02	0.0000	0.0000
8	0.3830E-02	0.2180E-02	0.4370E-02	0.1000E-03	1.571
10	0.2500E-03	0.0000	0.0000	0.0000	0.0000

********** ELEMENT AXIAL FORCE AND AXIAL TORQUE -- NONE

********** ANALYSES REQUESTED **********

********** WHIRL SPEED ANALYSIS FOR SPIN SPEEDS (Precessional mode plots requested)

	STARTING AT	5000.0	RPM	= 523.60	RAD/SEC	= 83.333	HZ
SHAFT 1	ENDING AT	5000.0	RPM	= 523.60	RAD/SEC	= 83.333	HZ
	INCREMENTED BY	4500.0	RPM	= 471.24	RAD/SEC	= 75.000	HZ

********** UNBALANCE RESPONSE, RIGID FOUNDATION, FOR SPIN SPEEDS

	STARTING AT	2500.0	RPM	= 261.80	RAD/SEC	= 41.667	HZ
SHAFT 1	ENDING AT	10000.	RPM	= 1047.2	RAD/SEC	= 166.67	HZ
	INCREMENTED BY	2500.0	RPM	= 261.80	RAD/SEC	= 41.667	HZ

Figure 4.—(Cont.).

Bently rig
Unbalance response with magnetic bearing & backup bearing

********** WHIRL SPEED AND STABILITY ANALYSIS **********

SHAFT 1 SPIN SPEED = 5000.00 RPM = 523.60 RAD/SEC = 83.333 HZ

8 PRECESSIONAL MODES AND 0 PURE REAL MODES

********** PRECESSIONAL MODES **********

MODE NO	************ FREQUENCY ************ RPM	RAD/SEC	HZ	DAMPING COEFFICIENT	LOG DECREMENT
1	1504.42	157.54	25.074	-15.154	0.60439
2	1579.42	165.40	26.324	-19.880	0.75522
3	2541.33	266.13	42.356	-128.02	3.0225
4	2703.01	283.06	45.050	-130.39	2.8943
5	4963.99	519.83	82.733	-176.21	2.1299
6	4974.02	520.88	82.900	-194.60	2.3475
7	6853.40	717.69	114.22	-185.05	1.6201
8	7882.47	825.45	131.37	-233.29	1.7758

*** PRECESSIONAL MODE 1: WHIRL SPEED = 1504. RPM = 157.5 RAD/SEC = 25.1 HZ. LOG DECREMENT = 0.604

(+,-) SEMI-MINOR AXIS INDICATES (FORWARD,BACKWARD) PRECESSION

			****** LEFT END TRANSLATION ********			****** RIGHT END TRANSLATION *******		
	ELEM NO	SUBELEM NO	SEMI-MAJOR AXIS	SEMI-MINOR AXIS	ATTITUDE ANGLE	SEMI-MAJOR AXIS	SEMI-MINOR AXIS	ATTITUDE ANGLE
SHAFT 1								
	1	1	0.3551	-0.3551	-162.3	0.3594	-0.3594	166.6
	2	1	0.3594	-0.3594	166.6	0.4536	-0.4536	142.7
	3	1	0.4536	-0.4536	142.7	0.5962	-0.5962	128.6
	4	1	0.5962	-0.5962	128.6	1.000	-1.000	112.7
	5	1	1.000	-1.000	112.7	1.091	-1.091	108.3
		2	1.091	-1.091	108.3	0.8485	-0.8485	107.1
	6	1	0.8485	-0.8485	107.1	0.6999	-0.6999	107.1
	7	1	0.6999	-0.6999	107.1	0.5466	-0.5466	107.2
		2	0.5466	-0.5466	107.2	0.3026	-0.3026	108.4
	8	1	0.3026	-0.3026	108.4	0.9669E-01	-0.9669E-01	116.1
	9	1	0.9669E-01	-0.9669E-01	116.1	0.2293	-0.2293	-79.93

*** PRECESSIONAL MODE 2: WHIRL SPEED = 1579. RPM = 165.4 RAD/SEC = 26.3 HZ. LOG DECREMENT = 0.755

(+,-) SEMI-MINOR AXIS INDICATES (FORWARD,BACKWARD) PRECESSION

			****** LEFT END TRANSLATION ********			****** RIGHT END TRANSLATION *******		
	ELEM NO	SUBELEM NO	SEMI-MAJOR AXIS	SEMI-MINOR AXIS	ATTITUDE ANGLE	SEMI-MAJOR AXIS	SEMI-MINOR AXIS	ATTITUDE ANGLE
SHAFT 1								
	1	1	0.4021	0.4021	-145.4	0.4200	0.4200	-119.9
	2	1	0.4200	0.4200	-119.9	0.5073	0.5073	-100.0
	3	1	0.5073	0.5073	-100.0	0.6358	0.6358	-87.03
	4	1	0.6358	0.6358	-87.03	1.000	1.000	-70.79
	5	1	1.000	1.000	-70.79	1.063	1.063	-65.96
		2	1.063	1.063	-65.96	0.8204	0.8204	-64.62
	6	1	0.8204	0.8204	-64.62	0.6773	0.6773	-64.64
	7	1	0.6773	0.6773	-64.64	0.5302	0.5302	-64.75
		2	0.5302	0.5302	-64.75	0.3000	0.3000	-65.96
	8	1	0.3000	0.3000	-65.96	0.1079	0.1079	-72.67
	9	1	0.1079	0.1079	-72.67	0.1970	0.1970	123.8

Figure 4.—(Cont.).

Unbalance response with magnetic bearing & backup bearing

*********** STEADY SYSTEM RESPONSE DUE TO SHAFT 1 UNBALANCE ***********

SHAFT 1 SPIN SPEED = 5000.00 RPM = 523.60 RAD/SEC = 83.333 HZ

		******* LEFT END DISPLACEMENT *******			******* RIGHT END DISPLACEMENT *******		
ELEM NO	SUBELEM NO	SEMI-MAJOR AXIS	SEMI-MINOR AXIS	ATTITUDE ANGLE	SEMI-MAJOR AXIS	SEMI-MINOR AXIS	ATTITUDE ANGLE
SHAFT 1							
1	1	0.1584E-03	0.1584E-03	64.16	0.1051E-03	0.1051E-03	72.57
2	1	0.1051E-03	0.1051E-03	72.57	0.5834E-04	0.5834E-04	95.95
3	1	0.5834E-04	0.5834E-04	95.95	0.4633E-04	0.4633E-04	159.9
4	1	0.4633E-04	0.4633E-04	159.9	0.1383E-03	0.1383E-03	-152.0
5	1	0.1383E-03	0.1383E-03	-152.0	0.1106E-03	0.1106E-03	-164.4
	2	0.1106E-03	0.1106E-03	-164.4	0.4297E-04	0.4297E-04	144.4
6	1	0.4297E-04	0.4297E-04	144.4	0.3567E-04	0.3567E-04	94.09
7	1	0.3567E-04	0.3567E-04	94.09	0.5337E-04	0.5337E-04	55.92
	2	0.5337E-04	0.5337E-04	55.92	0.8580E-04	0.8580E-04	29.37
8	1	0.8580E-04	0.8580E-04	29.37	0.1109E-03	0.1109E-03	14.08
9	1	0.1109E-03	0.1109E-03	14.08	0.1575E-03	0.1575E-03	-0.4621

*********** BEARING REACTIONS DUE TO UNBALANCE ***********

			*********** BEARING FORCES *************			*********** BEARING MOMENTS ************		
STN1	STN2	LOCATION	SEMI-MAJOR AXIS	SEMI-MINOR AXIS	ATTITUDE ANGLE	SEMI-MAJOR AXIS	SEMI-MINOR AXIS	ATTITUDE ANGLE
3	0	3.000	0.3385E-01	0.3385E-01	160.4	0.0000	0.0000	0.0000
9	0	24.00	0.1606	0.1606	60.40	0.0000	0.0000	0.0000

Figure 4.—(Concluded).

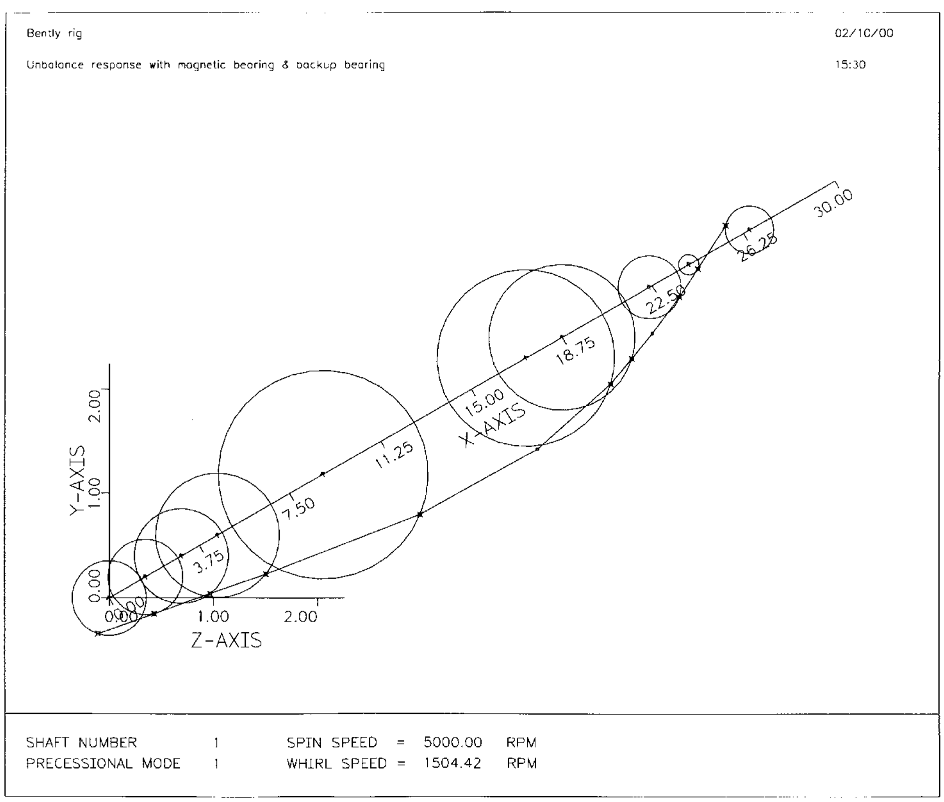


Figure 5.—First (backward) mode for example rotor.

maximum speed of the rotor system ranged up to 7882 rpm. The mode of figure 5 shows considerable rotor bending, as is expected from the small-diameter shaft and large attached masses. The nonlinear backup bearing does not enter in to the precessional mode calculations.

Example 2. Transient analysis of rotor drop onto backup bearing

For a magnetically suspended rotor, it is important to determine the dynamic behavior of the rotor if the magnetic support fails and the rotor drops onto the backup bearing. The situation is somewhat similar to that of a rub induced by a sudden unbalance such as caused by blade loss. Rotor drop is simulated in ARDS by specifying acceleration of the rotor base, and conducting a transient analysis. The input file for this case is shown in figure 6. The rotor system is the same as for example 1. Figure 7(a) plots the displacement at station 5 (near the rotor midpoint) for a friction coefficient of 0.5 in the backup bearing. The magnetic bearing is shut off at time zero, and the balanced rotor drops due to gravity. The plot covers 50 revolutions of the rotor. ARDS draws a small circle on the plot every 100 plotted points. Since the input specifies a calculation time step which yields 100 time steps per revolution, and directs ARDS to plot every 50th calculated point, the circles appear every 50 revolution.

It is apparent from figure 7(a) that the rotor motion has nonharmonic content. However, from this figure one cannot discern the period of motion or even whether the motion is periodic. More information can be obtained from a Poincaré plot, which produces a picture similar to what one would see if the rotor were illuminated by a strobe light. That is, the position of the rotor is recorded at periodic intervals. A Poincaré plot, showing the position of the rotor once per revolution, appears as figure 7(b) for the same simulation as figure 7(a). One can now see that the motion is periodic, with a period equal to four revolutions.

The Poincaré plot was produced via a kode 98 line in the input file followed by additional input data. The transient analysis time step and plot interval were selected to plot a point once per revolution (every 100 time steps, kode 13 line), while setting the third field of the kode 36 lines to 2.

Example 3. Sensitivity of response to parameter changes

When designing a rotor system, it is often desirable to have a set of sensitivity coefficients which quantitatively predict changes in specific system characteristics as design parameters change. The dynamic characteristics of usual interest are the system whirl frequencies, the critical speeds, and steady unbalance response. With the finite element analysis used by ARDS, the sensitivity coefficients (partial derivatives of system characteristics with respect to parameter changes) can be calculated. The parameters considered are bearing coefficients, inertial properties of concentrated masses (discs), and the distributed mass and stiffness of the rotating shafts.

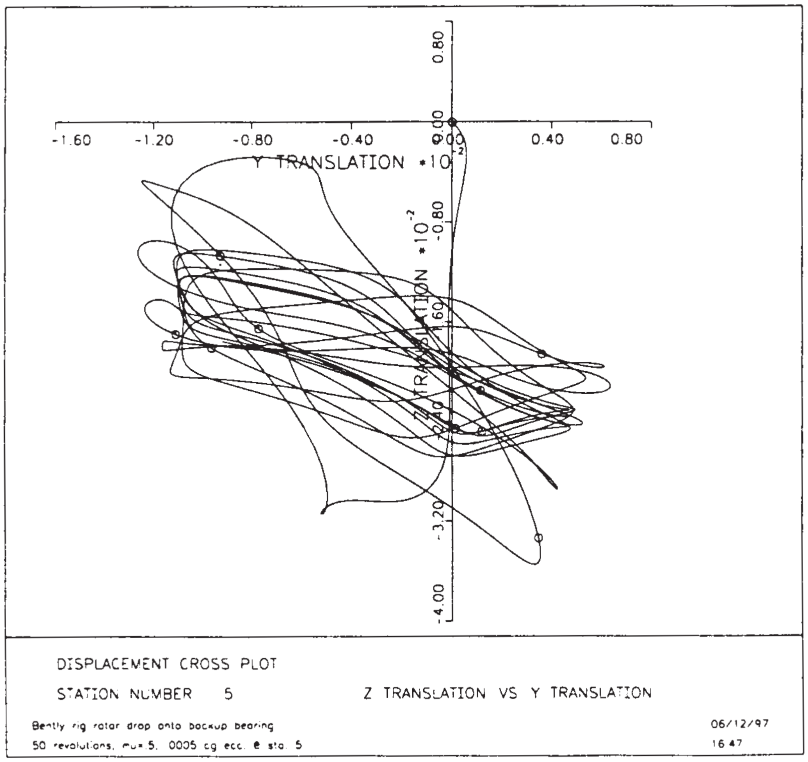
A NASA Glenn rotordynamics test rig was modeled for this exercise. The model of the shaft drawn by ARDS appears as figure 8. This rig has a slender shaft with three discs at stations 1, 4, and 7. The discs indicated in the figure at stations 2 and 6 represent the masses of the bearing housings, and are much smaller than the others. Figure 9 is the ARDS input file which uses customary U.S. units. Excerpts of printed output are shown as figures 10 and 11.

Figure 10 gives the sensitivity of the first critical speed (764 rad/sec for the base conditions) to changes in several system parameters. The rotor system analyzed is symmetric end-to-end; therefore sensitivity coefficients for, e.g., station 2 also apply to station 6.

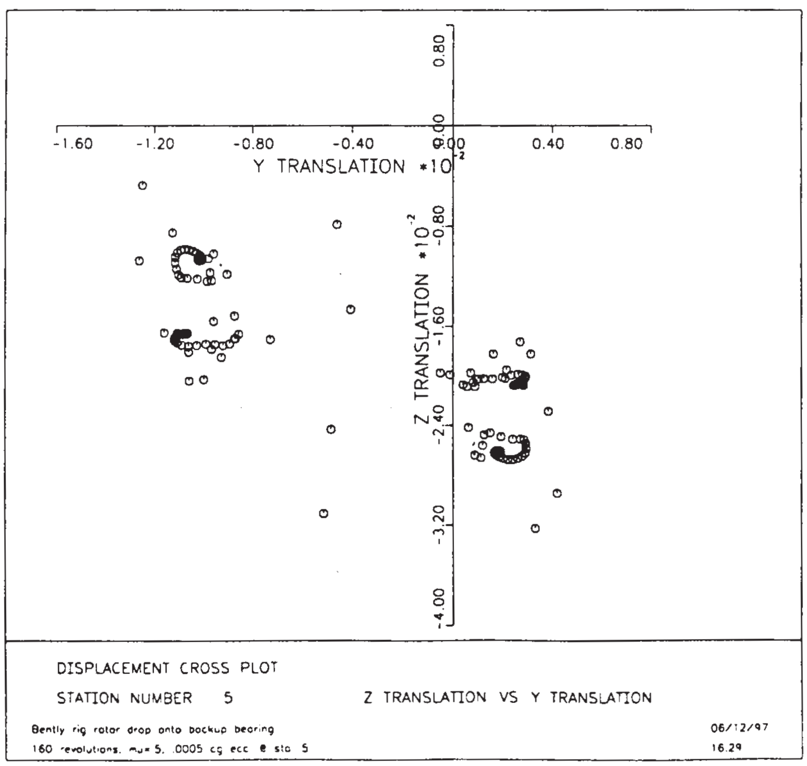
Program output is interpreted as follows. The damped critical speeds requested (in this case 4) are presented. Following that is a table showing the size of parameter changes used in calculating the sensitivity coefficients. ARDS allows the size of the parameter changes to be specified to make interpretation of output easier. For the example presented, large changes were specified, in most cases 100 percent of the base values. Since the sensitivity analysis calculates derivatives, the size of the change used is arbitrary, although the response to such changes is not generally linear.

```
Bently rig rotor drop onto backup bearing
50 revolutions, mu=.5, .0005 cg ecc. @ sta. 5
  1  0  0  1
  0  1       .000733     30000000.   15400000.   1.08
 25  1  1 10 0.
 26  1       6000.
 27  1  2  2 1000.       10000.
  1  1  1          1.5                   .1875   1.
  1  2  1          1.5                   .3125   1.
  1  3  1          1.5                   .3125   1.
  1  4  1          4.375                 .1875   1.
  1  5  1          4.375                 .1875   1.
  1  5  2          4.                    .1875   1.
  1  6  1          1.5                   .3125   1.
  1  7  1          1.5                   .3125   1.
  1  7  2          2.125                 .1875   1.
  1  8  1          1.625                 .1875   1.
  1  9  1          2.5                   .1875   1.
  2  3        .00207      .00057      .00114
  2  5        .00383      .00218      .00437
  2  7        .00207      .00057      .00114
  2  8        .00383      .00218      .00437
  2 10        .00025
  5  3  0  0 2.5                                 2.5
  5  9         1000.                              1000.
  7  3  0  0 .01                                 .01
  7  9         .5                                   .5
* Kode 13 calls transient analysis.
 13100  5   0.00010    .5
* Kode 14 specifies types of transient analysis.
 14  2     1 .00010     386.1       90.
 14  2     2 1.60       386.1       90.
 14  4  5  0 .00383     .0005
* Kode 42 invokes interference rub simulator in transient analysis.
 42  3  0  0 5000.      .5          .01
* Kodes 36 & 38 call transient output plots.
 36  3  1   2.                      1.
 36  5  1   2.                      1.
 36  8  1   2.                      1.
 38  3  1   2.                      1.
* Kode 98 denotes end of data for this case; another case to follow.
 98
160 revolutions, mu=.5, .0005 cg ecc. @ sta. 5
* First header line is not repeated for continuation case.
  1  0  0  1
 13100100    0.00010     1.60
 14  2     1 .00010     386.1       90.
 14  2     2 1.60       386.1       90.
 14  4  5  0 .00383     .0005
 42  3  0  0 5000.      .5          .01
* 2 in field 3 of kode 36 line produces Poincare plots
 36  3  2   2.                      1.
 36  5  2   2.                      1.
 36  8  2   2.                      1.
 36  9  2   2.                      1.
 99
```

Figure 6.—ARDS input for example 2 (rotor drop onto backup bearing).



(a) Orbit plot.



(b) Poincare´ plot.

Figure 7.—Rotor drop onto backup bearing.

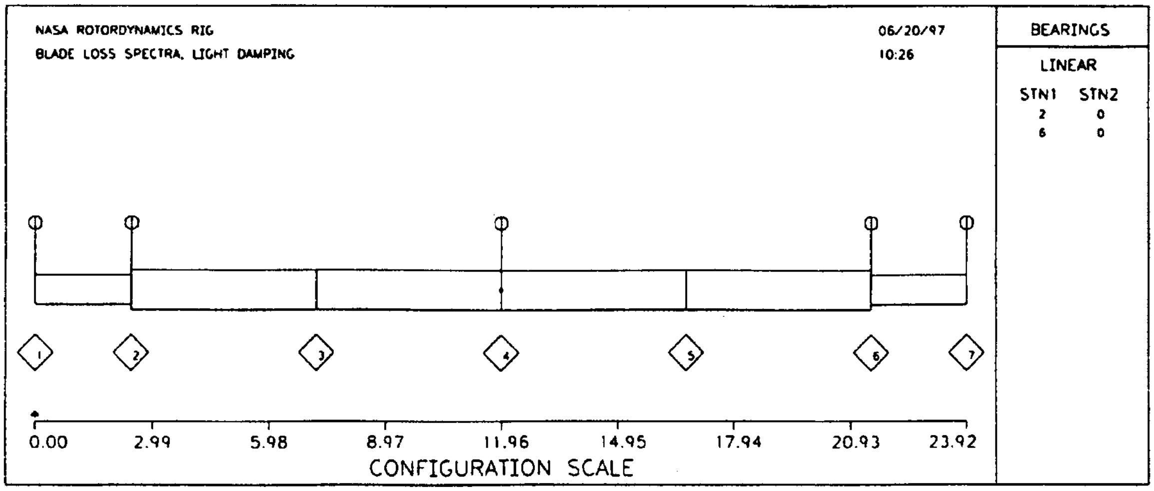


Figure 8.—ARDS plot of NASA rotordynamics rig.

```
NASA ROTORDYNAMICS RIG
SENSITIVITY DATA
  0  1  1  1
  0  1      .00074076   30000000.   15400000.   1.08
 25  1  1  7  0.
  1  1  1  1      2.45                  0.375    1.
* 1 in column 12 (fourth field) invokes sensitivity analysis.
* Similar for kode 2, 4-8 lines.
  1  2  1  1      4.754                 0.500    1.
  1  3  1  1      4.754                 0.500    1.
  1  4  1  1      4.754                 0.500    1.
  1  5  1  1      4.754                 0.500    1.
  1  6  1  1      2.45                  0.375    1.
  2  1     1  .0040693    .0035578    .0071156
  4  1  1  3 .002        0.
  4  4  4  3 .002        0.
  4  7  7  3 .002        0.
  2  2     1  .00030795
  2  4     1  .0040693    .0035578    .0071156
  2  6     1  .00030795
  2  7     1  .0040693    .0035578    .0071156
  5  2     1    10000.                             10000.
  5  6     1    10000.                             10000.
  7  2     1    2.                                 2.
  7  6     1    2.                                 2.
  9  1  1  0 6000.       12000.     2000.      1.
* 1 in last field invokes sensitivity analysis for kode 9 analysis
 10  1  1 -6 12000.      12000.     6000.      1.        1.
* 1 in last field includes whirl speed in sensitivity analysis.
 15  1  4   1.           0.         500.       1.        2.
* Kode 15 invokes sensitivity analysis for damped critical speeds.
 76  3      1.         4.         7.
* Kode 76 line lists output stations for unbalance response sensitivity.
 77  1      .00407     .00356     .00712     .002      10.
 77  2      10000.     1.         2.         1.
 77  3      1.         .0005818   1500000.
* Kode 77 lines contain multipliers for sensitivity analysis.
 99
```

Figure 9.—ARDS input for example 3 (rotor sensitivity factors).

```
****************  DAMPED CRITICAL SPEEDS, SYNCHRONOUS WITH SHAFT  1   ****************

NO    ***************  SHAFT(1) SPIN SPEED  ***************       DAMPING COEFFICIENT
 1      7296.74    RPM  =   764.11    R/S  =    121.6     HZ            -33.9000
 2      7352.10    RPM  =   769.91    R/S  =    122.5     HZ            -36.4016
 3      9258.14    RPM  =   969.51    R/S  =    154.3     HZ            -88.1485
 4      9465.02    RPM  =   991.17    R/S  =    157.8     HZ            -92.4001

************************* DAMPED CRITICAL SPEED SENSITIVITY ANALYSIS *************************
                       * * * * * * * * * * * * * * * * * * * * * * *
                       *      Output values in the following        *
                       *    sensitivity analyses are associated     *
                       *    with changes of the magnitude shown     *
                       *         for each listed parameter          *
                       *                                            *
                       *  **  PARAMETER  **    **  CHANGE UNIT  **  *
                       *                                            *
                       *   RIGID DISC                               *
                       *      Mass                 0.40700E-02      *
                       *      Diametral inertia    0.35600E-02      *
                       *      Polar inertia        0.71200E-02      *
                       *      CG eccen             0.20000E-02      *
                       *      CG angle              10.000          *
                       *                                            *
                       *   BEARING                                  *
                       *      Stiffness(trans)      10000.          *
                       *      Stiffness(rot)        1.0000          *
                       *      Damping(trans)        2.0000          *
                       *      Damping(rot)          1.0000          *
                       *                                            *
                       *   SUBELEMENT                               *
                       *      Length                1.0000          *
                       *      Unit mass            0.58180E-03      *
                       *      Bending stiffness    0.15000E+07      *
                       * * * * * * * * * * * * * * * * * * * * * * *

**** CRITICAL SPEED NO  1

SHAFT (1)  SPIN SPEED=   764.11    R/S

                    **********  RIGID DISC SENSITIVITY COEFFICIENTS **********

                    STN         MASS             DIAM.              POLAR
                     NO                          INERTIA            INERTIA
                      1        -7.4135           -0.75017            -1.5295
                      4        -125.84           -0.75851E-30        -0.13174E-29

                ******************  BEARING SENSITIVITY COEFFICIENTS ******************

                **********  STIFFNESS  **********      ***********  DAMPING  ***********

STN1 STN2       KVV      KVW      KWV      KWW        CVV      CVW       CWV      CWW
 NO   NO
  2    0       55.23    11.92   -11.92    55.23      1.447   -8.521    8.521    1.447
  6    0       55.23    11.92   -11.92    55.23      1.447   -8.521    8.521    1.447

                 ***********  SHAFT ELEMENT SENSITIVITY COEFFICIENTS   ***********

                ELE SUBEL          LENGTH             UNIT MASS            EI
                 NO   NO
                  1    1           5.1401             -5.6636          -0.33616E-01
                  2    1          -38.217             -38.165           11.811
                  3    1          -38.155             -76.394           68.243
```

Figure 10.—Critical speed sensitivity coefficients.

******************* STEADY SYSTEM RESPONSE DUE TO SHAFT 1 UNBALANCE *******************

SHAFT 1 SPIN SPEED = 6000.00 RPM = 628.319 R/S = 100.000 HZ

STATION NO	SEMI-MAJOR AXIS	SEMI-MINOR AXIS	ATTITUDE ANGLE
1	0.990014E-03	0.990014E-03	-16.2020
4	0.181737E-02	0.181737E-02	-15.6806
7	0.990014E-03	0.990014E-03	-16.2020

******************** STEADY UNBALANCE RESPONSE SENSITIVITY ANALYSIS ********************

***** UNBALANCE RESPONSE SENSITIVITY COEFFICIENTS DUE TO RIGID DISC STATION NO 1 *****

*** C.G. ECCENTRICITY ***

STATION NO	SEMI-MAJOR AXIS	SEMI-MINOR AXIS	ATTITUDE ANGLE
1	0.841221E-03	0.841221E-03	4.49288
4	0.249459E-03	0.249459E-03	-2.04940
7	-0.101247E-03	-0.101247E-03	-0.862307

***** UNBALANCE RESPONSE SENSITIVITY COEFFICIENTS DUE TO RIGID DISC STATION NO 4 *****

*** C.G. ECCENTRICITY ***

STATION NO	SEMI-MAJOR AXIS	SEMI-MINOR AXIS	ATTITUDE ANGLE
1	0.250040E-03	0.250040E-03	-3.63057
4	0.131846E-02	0.131846E-02	4.09880
7	0.250040E-03	0.250040E-03	-3.63057

********** UNBALANCE RESPONSE SENSITIVITY COEFFICIENTS DUE TO BEARING SUPPORT **********

******* BEARING COEFFICIENTS BETWEEN STATIONS 2 AND 0 *******

STATION	******** STIFFNESS ********		******* DAMPING *******	
NO	AMPLITUDE	ATTITUDE ANGLE	AMPLITUDE	ATTITUDE ANGLE
1	-0.222391E-02	33.0850	-0.718388E-04	-16.1736
4	-0.186304E-02	18.6166	-0.742048E-04	-7.38093
7	0.122457E-03	4.24847	-0.922489E-05	0.890587

***** UNBALANCE RESPONSE SENSITIVITY DUE TO SHAFT SUBELEMENT BENDING STIFFNESS (EI) *****

ELE NO 1 SUBEL NO 1

STATION NO	SEMI-MAJOR AXIS	SEMI-MINOR AXIS	ATTITUDE ANGLE
1	-0.242712E-03	-0.242712E-03	-1.72391
4	-0.286551E-04	-0.286551E-04	0.246839
7	0.791026E-05	0.791026E-05	0.527836E-01

ELE NO 2 SUBEL NO 1

STATION NO	SEMI-MAJOR AXIS	SEMI-MINOR AXIS	ATTITUDE ANGLE
1	0.381831E-05	0.381831E-05	-0.310422
4	-0.747739E-04	-0.747739E-04	0.474326
7	0.152281E-05	0.152281E-05	0.268108

ELE NO 3 SUBEL NO 1

STATION NO	SEMI-MAJOR AXIS	SEMI-MINOR AXIS	ATTITUDE ANGLE
1	0.747387E-04	0.747387E-04	2.55804
4	-0.771583E-03	-0.771583E-03	1.38706
7	0.179561E-04	0.179561E-04	2.55872

Figure 11.—Unbalance response sensitivity coefficients.

Next the sensitivity coefficients for changes in disc properties are shown. The data show that for an increase of the disc mass at station 4 of the amount shown in the table (which equals the original mass), the first critical speed will drop by 126 rad/sec. Changes in diametral and polar inertia of this disc have virtually no effect, because the first mode is symmetric, and station 4 is the midpoint of the shaft.

Sensitivity coefficients for bearing changes are then shown. Figure 10 shows that an increase of 10 000 (lb/in.) of direct stiffness in one bearing will increase the critical speed by 55 rad/sec, while an increase of 2 (lb-sec/in.) direct damping will increase the critical speed by only 1.4 rad/sec. Sensitivity coefficients for cross-coupled bearing coefficients are also calculated.

This section of sensitivity output concludes by showing changes in critical speed due to changes in shaft element length, unit mass (mass per unit length), and stiffness.

It is appropriate to state again that the sensitivity analysis calculates derivatives; results are thus strictly applicable for only small changes in parameters. The large changes of the example are for ease of interpreting results.

Figure 11 shows sensitivity of unbalance response to changes in various parameters. Center of gravity (cg) eccentricities of 0.05 mm (0.002 in.) were assumed for each of the three discs. Response to the original unbalance at the shaft speed chosen (6000 rpm in this case) is shown first. This is followed by change in response due to unbalance changes at the discs (these changes are shown on the change unit panel of fig. 10). The data show that unbalance at station 4 has a greater effect on response than that at station 1 (and also, because of the symmetric system, at station 7).

The next section deals with the effect of bearing properties. Again because of the symmetric system, the two bearings affect the response equally; only that for the bearing at station 2 is shown. The results show that increasing the stiffness of either bearing produces a large increase in the unbalance response. Changes in bearing damping have a much smaller effect.

Finally, changes in response due to changes in shaft element stiffness are shown. Shaft stiffness has a significant effect on response, as would be expected from the large amount of shaft bending indicated in the response to initial unbalance.

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13. ABSTRACT ***(Maximum 200 words)***

Personal computers (PCs) are now used extensively for engineering analysis; their capability exceeds that of mainframe computers of only a few years ago. Programs originally written for mainframes have been ported to PCs to make their use easier. One of these programs is ARDS (**A**nalysis of **R**otor**D**ynamic **S**ystems) which was developed at Arizona State University (ASU) by Nelson et al. to quickly and accurately analyze rotor steady state and transient response using the method of component mode synthesis. The original ARDS program was ported to the PC in 1995. Several extensions were made at ASU to increase the capability of mainframe ARDS. These extensions have also been incorporated into the PC version of ARDS. Each mainframe extension had its own user manual generally covering only that extension. Thus to exploit the full capability of ARDS required a large set of user manuals. Moreover, necessary changes and enhancements for PC ARDS were undocumented. The present document is intended to remedy those problems by combining all pertinent information needed for the use of PC ARDS into one volume.

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